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PACKAGING SYSTEMS

Environmental impacts of conventional plastic and bio-based carrier bags

Part 2: end-of-life options

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Abstract
Background, aim, and scope Worldwide, the production of biodegradable and compostable plastics has steadily grown. In Part 1 (Khoo et al. 2010), life cycle assessment (LCA) was applied to compare the production stages of a bio-based bag (made from polyhydroxyalkanoate or bio-plastic (PHA)) with polyethylene plastic bag. The scope of the study is within the context of Singapore and does not include other types of conventional or bio-based polymers (e.g., polylactic acid (PLA), thermoplastics, high-density polyethylene (HDPE), EPS, etc). This article (part 2) proposes to investigate the end-of-life options of both bags.
Materials and methods For part 2, the same LCA methodology is used for the investigation. The LCA system for part 2 starts with disposal options: (1) land filling at Singapore's offshore Semakau Island, (2) incineration, and the (3) composting of bio-bag. Two useful products, energy and compost, will be produced from options 2 and 3, respectively. While the energy from the incineration of both bags are fed back into the LCA production stage, compost from bio-bags can be used as a peat substitute, thus generating carbon dioxide savings from reduced peat production. The end-of-life environmental impacts were generated for global warming potential, acidification, and photochemical ozone formation. A landfill impact, based on Singapore's offshore landfill capacity, was also generated. Next, the environmental impacts of the entire life cycle of both products are calculated for a few scenarios—from cradle-to-grave.
Results The highest end-of-life impacts are observed from the land filling of bio-bags. Next highest disposal impacts are from incineration, and least of all (minimal) from the composting of bio-bags. The greenhouse gas savings from peat substitutes derived from the compost material is rather insignificant. Overall, the cradle-to-grave results demonstrates that the environmental burdens generated from any of the disposal options are less significant compared to those from both products' life cycle production stages.
Discussion and conclusions Unless plans for energy recovery systems are in place, the least preferred route for the disposal of bio-bags are at landfills. From the trend of the final cradle-to-grave results, it can be claimed that the life cycle production of bio-bags from PHA can only be considered as environmentally friendly alternatives to conventional plastic bags if clean energy sources are supplied throughout its production processes. This claim was in agreement with other LCA work carried out for the life cycle production of PHA, with the supply of energy by corn stover waste or the consideration of wind power supply in the replacement of grid electricity. It was also observed, however, that some of the results in this article vary from other LCA work carried out by other authors. Some of the reasons included variations in LCA scope and the different range of materials investigated (PLA, HDPE, and thermoplastic starch).
Recommendations and perspectives Presently, the wide range of LCA work carried out on biodegradable polymers differs considerably in the amount of reported background data and the level of detail concerning the LCA system and

Part 1: life cycle production

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production methods. A globally accepted as well as concerted effort to describe in detail the life cycle production steps involved, disposal options, type of energy supplied to the production chain, for a well-selected range of polymer materials should be conducted. Meanwhile, it is recommended that a conservative approach is required in introducing bio-based carrier bags as a solution for solving plastic waste issues. Future LCA investigations should also look into the reuse of carrier bags, which is anticipated to bring much greater environmental and sustainable benefit than the replacement of bio-bags with plastic ones.

Keywords Bio-plastic (PHA) · Composting · End-of-life · Incineration · Landfill · Polyethylene plastic (PP)

1 Background, aim, and scope

The shift away from petroleum-based polymers to renewable feedstock for making plastics provides many opportunities in the field of industrial biotechnology (Hatti-Kaul et al. 2007). The applications of bio-based polymers emerged since 1980s and are now gaining more attention worldwide since they can be made from renewable resources, thus reducing the reliance on fossil fuels. The concept to produce green environmentally products is a cyclic one, where sunlight, carbon dioxide (CO_2) and other inputs are absorbed during the growth of feedstock (crops) for making bio-plastics. After use, the disposed bio-plastic can biodegrade into natural substances that can be applied as peat substitutes or in some other, fertilizers. A schematic diagram of some of the process involved is illustrated in Fig. 1 (Gross and Kalra 2002). Conventional plastics made from fossil fuels persist for many years after disposal. In

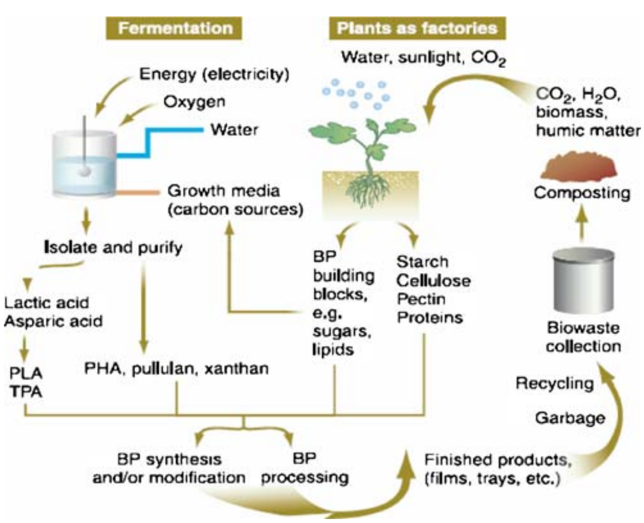

Fig. 1 Cyclic processes of bio-based products

Fig. 2 Aerial view of Semakau landfill

contrast, bio-bags are biodegradable and can decompose in the correct environment containing microorganisms such as bacteria and fungi. Polyhydroxyalkanoates or bio-plastic (PHA)-based plastics have the advantage of being completely compostable in many environments (Comstock et al. 2004).

1.1 Management of municipal solid wastes

As a small city-state with a growing and rigorous industry, Singapore is challenged with managing its waste disposal facilities effectively. With a total mainland area of 647.5 km^2**,** the nation is faced with limited land for the dumping of wastes. The annual generation of municipal solid waste from households and industries has increased steadily from 2.76 to 2.79 million tons in years 1996 and 2000, respectively, and to an overwhelming 5.22 million tons in 2006. Out of these amounts, 12% waste consists of plastics (NEA 2008).

Presently, Semakau Landfill is Singapore's only landfill for waste disposal. It covers a total area of 350 ha and has a landfill capacity of 63 million m^3. The Pulau Semakau island is situated 25 km offshore from the south of mainland Singapore. Commissioned in the year 1999, the landfill's lifespan is expected to last until the year 2030. An aerial view of Semakau Landfill is displayed in Fig. 2.

The modeling of Land Impacts in life cycle assessment (LCA) is yet to be established. In practice, there is still no commonly accepted solution on how to model landfills in the LCA of waste management (Obersteiner et al. 2007). In this report, a simplified estimation of land use will be made based on the area occupied by wastes. Site-dependent impacts should be incorporated within an LCA case study in order to make the results more meaningful. However, land impacts have not been part of any well established LCIA models, for example, see Fig. 2.

2 Life cycle assessment: end-of-life options

Life cycle assessment is a tool for measuring the environmental sustainability and environmental performance-

improvement opportunities of products (Dewulf and van Langenhove 2002). In part 1, a typical bio-based plastic made from corn is selected to be compared with plastics made from polypropylene plastics (PP). While the first LCA is carried out for cradle-to-gate, the next analysis looks into various end-of-life options, including landfill, incineration for both materials and composting for bio-plastics.

2.1 LCA scope, functional unit and system boundary

The LCA work will is carried out in the following end-of-life scenarios:

- landfill,
- incineration,
- composting (bio-bag only),
- finally, an overall cradle-to-grave comparison is made for several scenarios.

The functional unit for each bag, based on a "standard bag" with carrying capacity of 20 kg, are 4.90×10^{-3} kg for PP bag and 9.03×10^{-3} kg for bio-bag (from part 1). For the land filling of wastes, the PP or bio-bags have to first be transferred 25 km offshore by barge, before being unloaded and compacted. The reported energy required for land filling processes, including the compaction and loading, is 38 MJ per ton waste. The LCA system boundary, from the use stage to end-of-life is shown in Fig. 3. Two useful products can be produced—energy from incineration from both plastic and bio-based material, and peat from the composting of bio-based bags. The compost product can be used as peat substitution (Kale et al. 2007).

Since there is presently no composting facility in Singapore for biodegradable or compostable plastic products, the last end-of-life route is a theoretical option. Again, a few assumptions have to be established for the LCA waste system:

- the PHA is compostable in nature and can be turned to compost under appropriate composting conditions. The compost produced (wet basis) is can be used as peat substitution,
- zero energy is consumed during the use phase of both types of bags,
- the transportation by road from the use stage to the incinerator, landfill transfer station, or composting facility covers more or less the same distance, so this can be conveniently omitted,
- emissions to air include CO_2, CH_4, acidic gases, HF and HCl from incineration and landfills, and CO_2, CH_4, N_2O, NH_3 and VOC from the composting of biodegradable wastes,
- in the landfill, it is assumed that 50% of bio-bag will decompose, due to lack of microbes and other organisms that aid in the breaking down of bio-materials.

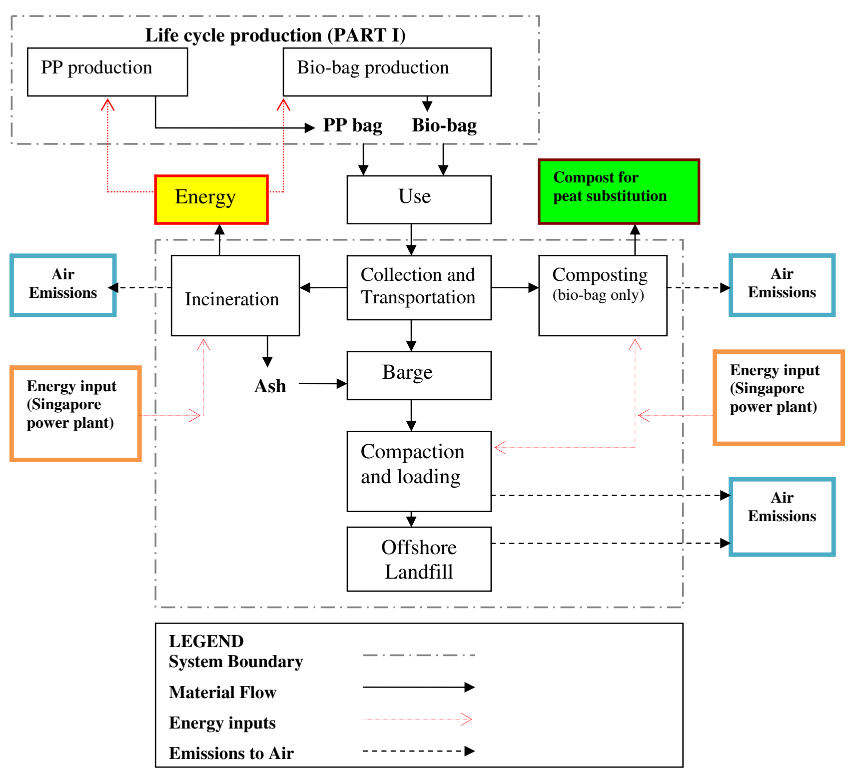

Fig. 3 LCA system for end-of-life options

Table 1 Landfill and incineration emissions

Air emissions (kg/kg waste material)	Conventional plastics		Bio-plastics	
	Landfill	Incineration	Landfill	Incineration
CO_2	5.30E-02	2.61E+00	2.69E-01	5.37E-01
CH_4	1.90E-02	2.34E+00	9.94E-02	5.37E-01
NOx	4.00E-05	2.56E-08	2.62E-10	6.29E-09
SOx	9.48E-05	1.09E-08[a]	3.30E-11	2.68E-09
HCl	6.70E-08	5.19E-10[a]	n.a.	1.28E-10
HF	1.35E-08	2.70E-08	n.a.	1.00E-10

[a] After removal of SOx and NOx from modern day incinerators

2.2 Life cycle inventory

Landfill and incineration emissions for both materials are extracted from White et al. (1994) and Bjarnadóttir et al. (2002). These data are compiled in Table 1. The energy input required for incineration is 252 MJ per ton of plastic waste. Generally, polymers made from petroleum have higher calorific values than materials made from crops. The useful energies derived from plastic materials are reported to be 25 GJ per ton, and for bio-plastics, approximately 10 GJ/ton. All the energy supplied for the stages involved (see Fig. 3) is from Singapore electricity mix. The composting of biodegradable plastics, such as PHA, generates air emissions. Specific data for composting emissions are unavailable. General emission data, shown in Table 2, are taken from Lens et al. (2004) and Davis and Song (2006). Compost is produced from the bio-plastic, where about 1/3 of the compost product can be used as peat substitution. This in turn saves 188 kg CO_2-eq per ton peat (Kale et al. 2007; Schleiss 2008; Rudnick 2008).

3 Impact assessment results: end-of-life

The EDIP 2003 method (Hauschild and Potting 2003) is used to generate the results for global warming potential, acidification, and photochemical ozone formation. The results are displayed in Figs. 4, 5, and 6. Figure 4 highlights that if bio-bags are used to replace conventional plastic bags, the least preferred end-of-life route is at open landfills. During the process of breaking down, bio-bags in landfills generate methane gases. This is further confirmed by the work done on greenhouse gas generation from landfills (Davis and Song 2006; Machado et al. 2009).

Table 2 Composting emissions

Air emissions (kg/kg bio-bag)	Composting
CO_2	3.50E-01
CH_4	9.83E-04
N_2O	1.10E-05
NH_3	1.50E-05
VOC	7.80E-05

Also from Fig. 4, the incineration of PP bags generates about double the amount of greenhouse gases compared to the incineration of bio-bags. In the LCI data estimated from White et al. (1994) and Bjarnadóttir et al. (2002), the incineration of waste materials generates typically 2.61 kg of CO_2 plus 2.34 kg methane for every kg of plastics and 0.537 kg CO_2 plus 0.537 kg methane per ton of mixed bio-waste. A considerable amount of greenhouse gases are generated during composting (Schleiss 2008); however, they are slightly less than those from the incineration of bio-bags, and notably a great deal less than those from landfills. A small amount of CO_2 savings occurs from peat substitutes derived from the composting of bio-bags. However, this amount is rather insignificant due to the small fraction of peat (about 1/3) that can be generated from the compost product (Kale et al. 2007).

From Fig. 5, the acidic gases from PP bags are slightly higher in landfills than those from bio-bags. Modern day incinerators are equipped with SO_x and NO_x removal facilities, therefore the emissions to air from the incineration of both waste materials are minimal. The contribution to acidification impacts for composting is primarily from ammonia (NH_3) gases. Usually in composting facilities for mixed organics (food waste, garden waste, etc), ammonia emissions are uncontrollable and may be significantly higher (Bjarnadóttir et al. 2002). However, for bio-plastics, the

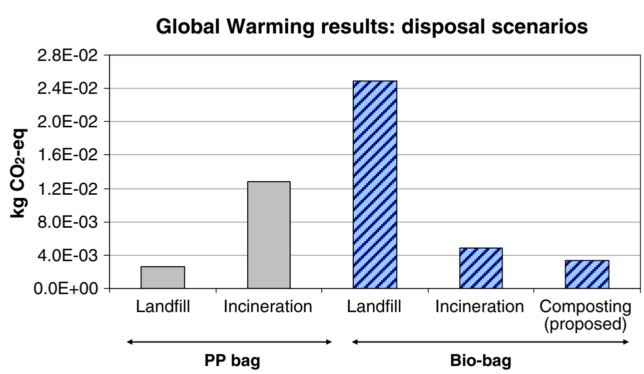

Fig. 4 Global warming results: end-of-life options

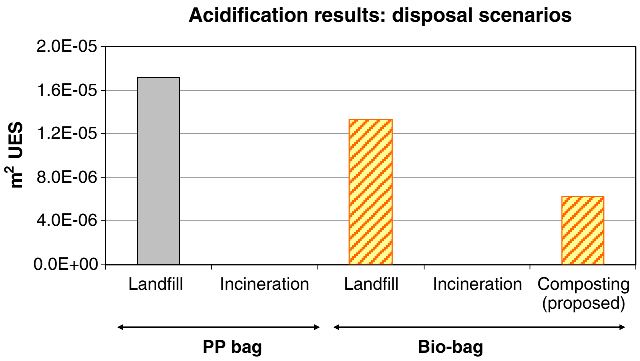

Fig. 5 Acidification results: end-of-life options

amount of NH_3 generated can be controlled to a considerably reduced amount (Rudnick 2008).

From Fig. 6, it is observed that bio-bags contribute significantly to photochemical ozone formation when land filled. This is due to the release of methane (CH_4) gases during the breakdown of carbon from biodegradable materials (Lombardi et al. 2006), which is the same reason for the high global warming results (see Fig. 4). The photochemical ozone formation result for PP bags placed in landfill is significantly less than those of bio-bags.

3.1 Impacts for landfill capacity

Currently there is no standard method or approach to model land use or landfill impacts (Obersteiner et al. 2007; Udo de Haes et al. 2002; Lombardi et al. 2006). A simplified landfill impact is proposed based on landfill capacity (alone). The land use impact for Semakau, based solely on capacity volume (m^3) for *inert waste*, is proposed as follows:

$$\sum V_x = \sum m_x(1/\rho_x)$$

where:

V_x the total volume (m3) occupied by waste type x
m_x the mass of waste x (kg)
ρ_x the density of waste x (kg/m^3)

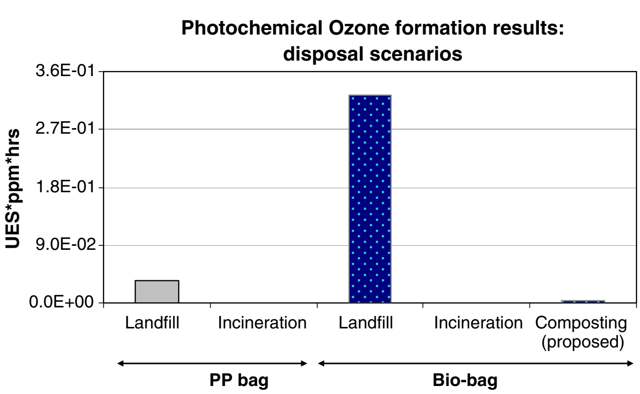

Fig. 6 Photochemical ozone formation results: end-of-life options

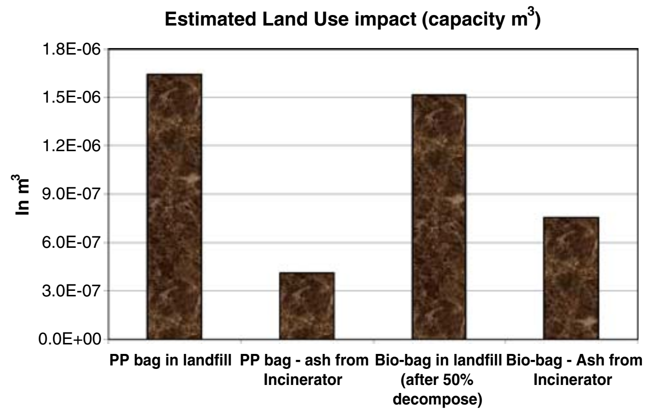

Fig. 7 Projected impacts for landfill use capacity

Semakau landfill has a capacity of 63 million m^3; and the reported bulk density of ash and residues = 1.5 g/cm3 or 1,500 kg/m^3. This implies that 1 kg of ash/residues will occupy a space of 0.00067 m^3. The landfill impact does not take into account the potential affect of residues/ashes on: loss of biodiversity, changes in soil quality, time-dependent accumulation of leaching, effects on human health and quality of life. The area of land occupied by peat amount generated from the composting of bio-bag is too insignificant to be considered and can be omitted from land use impacts (Dornburg et al. 2004).

The landfill impact results are displayed in Fig. 7. While the previous results display an environmental-type impact—based on substances released contributing to human health effects or the degradation of marine life and ecosystems—the present "Land Use" model characterizes a non-environmental form of impact.

3.2 Normalized results: cradle-to-grave

The normalized value for landfill capacity is estimated based on 1.46 million tons of wastes disposed in a year (NEA 2008). Given a population of 4.59 million people in 2007 (Government of Singapore 2008), this value translates to 318.08 kg/capita/year or 0.213 m3/capita/year. The normalized values are compiled in Table 3. The normalized results are generated for various production (part 1) to end-of-life options. The normalized data for global warming

Table 3 Normalization and weighting values for Singapore

Impact category	Normalization values for Singapore data
Global Warming	6200 (CO_2-eq/capita/year)
Acidification	894 (UES m^2/capita/year)
Ozone Photochemical Formation	85600 (person × ppm × h/capita/year)
Land use (capacity)	0.213 (m3/capita/year)

Table 4 Cradle-to-grave: production and end-of-life scenarios

Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Product	PP bags		Bio-bag			Bio-bag			Bio-bag			Bio-bag		
Energy supplied in production	Singapore grid electricity		US electricity grid mix			Coal-fired power			NGCC			Geothermal power		
End-of-life options	Landfill	Incineration	Landfill	Incineration	Compost	Landfill	Incineration	Compost	Landfill	Incineration	Compost	Landfill	Incineration	Compost

potential (CO_2-eq), acidification (UES square meter or area of unprotected ecosystem) and ozone photochemical formation (person × ppm or parts per million × hours) are compiled in Table 4. The results are displayed in Fig. 8.

The highest end-of-life impacts are from scenarios 3, 6, 9, and 12, where bio-bags are dumped at landfills. Next highest disposal impacts are from incineration, and least of all (minimal) from the composting of bio-bags. For scenario 2, it can be observed that the total production impacts are reduced by about 2/3 due to the energy derived from the incineration of the PP bag. The same benefit is realized from the incineration of bio-bags (scenarios 4, 7, 10, 13), but compared to polymers, not as much energy can be derived from biodegradable products (White et al. 1994). It is also noted that the composting of bio-bags (scenarios 5, 8, 11, and 14) offer very minimal greenhouse gas savings. Fertilizers derived from compost material are expected to bring about greater reductions in greenhouse gases due to substantial energy savings (from fertilizer production). However, such benefits are not obtained because the nature of compost material in this article can only be used as peat substitutes (Kale et al. 2007; Schleiss 2008; Rudnick 2008). Overall, the cradle-to-grave results demonstrates that the environmental burdens generated from any of the disposal options are less significant compared to those from both products' life cycle production stages (Khoo et al. 2010).

4 Discussions and conclusions

Bio-based materials have been introduced as an environmentally alternative to conventional plastics due to the fact that they are not made from limited fossil fuel resources and can breakdown in landfills (Hatti-Kaul et al. 2007; Gross and Kalra 2002). However, despite the assumptions that bio-bags are a better option than conventional plastic bags, an LCA study is required to demonstrate these claims

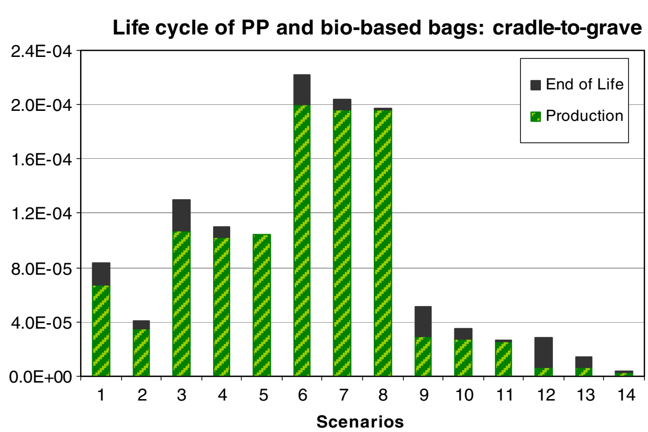

Fig. 8 Total environmental impacts from cradle-to-grave: production and end-of-life scenarios

from cradle-to-grave. The results from this article (see Figs. 4 and 6) illustrate that unless plans for energy recovery systems are in place, the least preferred route for the disposal of bio-bags are at landfills. An example of landfill energy recovery can be found in a study carried out by Lombardi et al. (2006), where the energy from methane gas was captured from the breaking down of biodegradable carbon compounds.

From the trend of the final graphs from (see Fig. 8, scenarios 3–14), it can be claimed that the life cycle production of bio-bags from PHA can only be considered as environmentally friendly alternatives to conventional plastic bags if clean energy sources are supplied throughout its production processes. This claim, as concluded in part 1, is supported by Kurdikar et al. (2001), who concluded that the use of corn stover waste as a renewable energy resource results in reduced environmental impacts for making PHA. Akiyama et al. (2003) echoes this view by considering wind power as a replacement of grid electricity in the life cycle production of PHA.

It is also observed, however, that some of the results in this study vary from other LCA work carried out by James and Grant (2005), Murphy and Bartle (2004), and Dornburg et al. (2004) on the environmental profiles of bio-polymer or biodegradable materials. A few reasons are offered to explain the differences. The publications differ considerably in their scope (system boundary), extent of life cycle stages (from cradle-to-gate or cradle-to-grave), and the range of materials investigated, e.g., polylactic acid, high-density polyethylene, thermoplastic starch, to name but at few. Since the work carried out by the authors in this article focuses on PHA and PP materials, the dissimilar studies (James and Grant 2005; Murphy and Bartle 2004) do not allow a consistent comparison of the LCA. It is also observed that, except for Kurdikar et al. (2001) and Akiyama et al. (2003), not all authors specify describe the exact sources of energy that is supplied to the bio-polymer production chain. Such lack of information, along with the disparate range of polymer choices of interest, does not allow us to make a justifiable comparison or conclusion from the collection of LCA work aimed at bio-materials.

5 Recommendations and perspectives

Before bio-based plastics can be recommended as an environmentally preferred option to plastics, a few challenges have to be overcome. The main issue lies in reducing the energy used in the life cycle production of the bio-material from crops (Khoo et al. 2010). There is presently a wide range of LCA work carried out on biodegradable polymers. However, the publications differ considerably in the amount of reported background data and the level of detail concerning the LCA system and production methods (Dornburg et al. 2004). A globally accepted as well as concerted effort to describe in detail the life cycle production steps involved, disposal options (landfill, composting, and incineration), type of energy supplied to the production chain (fossil fuel power or renewable energy resources), for a well-selected range of polymer materials should be conducted. Meanwhile, it is recommended that a conservative approach is required in introducing bio-based carrier bags as a solution for solving plastic waste issues. Future LCA investigations should also look into the reuse of carrier bags, which is anticipated to bring much greater environmental and sustainable benefit than the replacement of bio-bags with plastic ones.

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